Available online at www.sciencedirect.com
SCIENCE DIRECT®

Europ. J. Agronomy 18 (2003) 171–185

European Journal of Agronomy

www.elsevier.com/locate/eja

A framework for simulating agroforestry options for the low rainfall areas of Australia using APSIM

N.I. Huth [a,*], P.S. Carberry [b], P.L. Poulton [b], L.E. Brennan [a], B.A. Keating [a]

[a] *Agricultural Production Systems Research Unit (APSRU), CSIRO Sustainable Ecosystems, 120 Meiers Rd., Indooroopilly, Qld, 4068, Australia*

[b] *Agricultural Production Systems Research Unit (APSRU), CSIRO Sustainable Ecosystems, PO Box 102, Toowoomba, Qld, 4068, Australia*

Abstract

The long-term benefits of retaining or planting trees on farms to rehabilitate land and protect the soil from erosion or salinity problems has to be traded off against the impact of tree competition on commercial crops, especially in the medium to low rainfall regions of Australia. The incentive to plant trees would increase if tree competition could be offset by economic returns gained from farm forestry products and by the beneficial impacts of tree windbreaks on crop yields and resource sustainability. The Agricultural Production Systems Simulator (APSIM) has a well-established capability to simulate cropping systems and this paper reports on progress in applying APSIM to agroforestry systems in order to quantify the potential benefits and risks of planting trees as windbreaks to cropping land in Australia. A simple case study indicating one possible model configuration is used to demonstrate this emergent capability for simulating tree and crop productivity and their interactions. The simulated agroforestry system consisted of the growth of a belt of trees (*Eucalyptus argophloia*) positioned as a windbreak on the edge of a field where a crop of winter chickpea (*Cicer arietinum* L.) is grown over a 30-year period. The example simulations quantify the yield and economic returns of annual chickpea crops in addition to the discounted economic return from timber production after 30 years of tree growth. This example demonstrates how APSIM can be used to quantify the economic tradeoffs in planting trees as windbreaks on a commercial farm in a low rainfall region of Australia.

Keywords: APSIM; Simulation; Agroforestry; Wind breaks

1. Introduction

The salinisation of landscapes is among the greatest challenges to the dryland farming systems of Australia (NLWRA, 2000). As a consequence there is considerable interest in Australia for capturing the expected long-term benefits of retaining or planting trees on farms to rehabilitate land and protect the soil from erosion or salinity problems (Prinsley, 1992; Stirzaker et al., 2002). However, trees compete with commercial crops both for land area and resources, especially in the medium to low rainfall regions of Australia. The incentive for landholders to plant trees would

* Corresponding author. Tel.: +7-617-3214-2398; fax: +7-617-3214-2308.
E-mail address: neil.huth@csiro.au (N.I. Huth).

1161-0301/03/$ - see front matter.
PII: S1161-0301(02)00103-X

increase if crop losses could be offset not only by the beneficial impacts of tree windbreaks on crop yields and resource sustainability but also by the economic returns gained from farm forestry products. A significant problem in encouraging landholders to act on this incentive is that it is difficult to quantitatively assess this trade off between crop and tree productivity for different regions and cropping systems, and almost impossible for landholders to do so in the context of their own farm.

A number of recent research developments in Australia now provide the opportunity to enable the trade off between tree and crop productivity on farms to be quantified using systems simulation in a manner relevant to commercial farming practice. Firstly, within the Australian environment, the beneficial effect of tree windbreaks has been quantified and an ability to predict such effects has been developed (Cleugh, 2002; Meinke et al., 2002). Secondly, the ability to predict tree productivity has progressed to a point that is now comparable to current crop simulation models (Huth et al., 2001). And thirdly, considerable evidence now exists in Australia that simulation models can be regarded by farmers and consultants as viable and relevant tools in the management of their commercial farming enterprises (McCown et al., 1998). Many Australian farmers and several agribusiness firms regularly use the model to quantitatively assess alternative cropping strategies in the context of their own farm or business (Hochman et al., 2000).

There is increasing public pressure for more trees on farmlands, driven mainly by the land conservation and biodiversity benefits that accrue from planting trees. The cost of achieving this, however, falls largely on the farming community. Convincing evidence to support an economic benefit to farm productivity from retaining and/or planting trees on farms would greatly enhance the incentive for increasing the farmland under trees. Thus, the primary beneficiaries of a capability to explore relevant agroforestry design options are landholders who may be better able to assess the economic benefits that they can expect from integration of agroforestry enterprises into dryland cropping systems. Other beneficiaries from enhanced landholder investment in commercial agroforestry will include the Australian timber industry through increased production diversity and the broader community through improved land conservation.

This paper describes the capability being developed within the APSIM simulation framework (McCown et al., 1996; Keating et al., 2003) to simulate agroforestry systems in Australia. A simple case study indicating one possible model configuration is provided to demonstrate this emergent capability for simulating tree and crop productivity and their interactions within a variable climate.

2. Simulating agroforestry systems

A general characteristic of most agroforestry systems is the heterogeneity introduced by combining crops or pastures with a tree component. Conceptually, it may be possible to describe an agroforestry system as a series of discrete crop-based or tree-based components with flows of mass or energy between each component being dependent upon the states of the components. A simulation model based upon this conceptualisation would be required to not only simulate the dynamic processes within each component, but also dynamically describe the changes in interactions between components.

Many existing agroforestry models are based upon such abstraction of the crop–tree interface into discrete areas with defined interactions. The WaNulCAS model (Van Noordwijk and Lusiana, 1999), for example, utilises a series of soil zones to calculate subsurface competition between trees and crops at different distances from the trees in question. In a similar manner, the SBELTS model (Qi et al., 2001) simulates crop production at a range of discrete points down-wind of a windbreak in order to calculate a spatially integrated yield response to wind protection. In both cases, this simple abstraction of the system into functional units allows the application of existing simulation methodologies to be followed by simple integration to investigate overall system behaviour.

One possible constraint to such an approach might lie in the ability to bring together simulation capability from the differing disciplines into the one integrated framework (Jones et al., 2001). Matthews and Lawson (1997) combined existing tree (Hybrid, Friend et al., 1997) and cassava (GUMCAS, Matthews and Hunt, 1994) models in order to evaluate various agroforestry management options. This same tree model has been incorporated into the HyPAR model (Mobbs et al., 1997) which uses the tropical crop model PARCH (Fry and Lungu, 1996) to simulate crop growth. Lawson et al. (1995) used this combined framework to evaluate crop productivity under different environmental conditions using a wider range of existing tree canopy models (MAESTRO, Wang and Jarvis, 1990; ERIN, Wallace, 1996). Mayus et al. (1999a) drew upon existing models of crop growth, soil water flow and wind impacts. Qi et al. (2001) employed the CROPGRO (Boote et al., 1998) model in their predictions of soybean yield in windbreak systems. The Agroforestry Modelling Environment (Muetzelfeldt and Taylor, 1997) provides a graphical environment for combining simulation components and analyzing agroforestry configurations including spatial aspects. It appears that many agroforestry modelling efforts have taken the approach of combining existing crop and tree components and adding routines that account for their interactions. An ability to bring together existing simulation capabilities from various disciplines into a common modelling framework would be an attractive advancement for the simulation of agroforestry systems.

The Agricultural Production Systems Simulator (APSIM) (McCown et al., 1996) has been specifically designed to facilitate cross-disciplinary simulation-based research. A component-based design allows individual models to communicate via a common communications engine. At present, over 20 individual crop and pasture modules are available within APSIM for use in simulating diverse farming systems. These crop modules communicate with existing modules for simulating soil processes such as carbon, nitrogen and phosphorous cycling, surface residue dynamics, water and solute fluxes, soil temperature, and soil acidity. A forest production modelling capability has recently been added to APSIM (Huth et al., 2001). APSIM has been used to investigate competition for light and soil resources of intercropped plant species (Carberry et al., 1996) and also to investigate sheltering effects using traditional single point simulation methods (Carberry et al., 2002b). An updated description of the APSIM model is provided by Keating et al. (2003).

The modules within APSIM are essentially point-based models, which represent the behaviour of the system at some single point in space, or alternatively one discrete homogeneous area. Current developments on the inter-module communications protocol employed by APSIM (Wright et al., 1997) now allow the application of the model to issues that contain a spatial component. The new protocol allows multiple instances of groups of the point-based models within a single simulation with communication of data between each discrete point in space. An abstraction of an agroforestry system into functional units can thus be represented by a series of these instances with clearly defined data flows between each unit.

3. A conceptual agroforestry system

The introduction of windbreaks into cropping systems in the medium to low rainfall zones of Australia is an agroforestry system of interest to landholders and policy researchers. Such agroforestry systems usually consist of belts of trees planted along the borders of crop fields. The shelter introduced by these trees is thought to provide multiple benefits (Cleugh, 2002). These include the protection of the crops from wind damage or drift of pesticides from neighbouring fields, increased yield as a result of reduced water demand within the sheltered zone, shelter from wind and sun for livestock, and control of losses due to overland flow of runoff. This system can be conceptualised in two dimensions. Fig. 1 shows the principal components of such a system.

Windbreaks often consist of several rows of trees along the side of a field facing the prevailing winds. This belt of trees can be divided into two functional components (Albertsen et al., 2000). The roots of the trees on the edge of the tree belt have access to water and nutrients within the field and, as a result, the productivity of these trees is

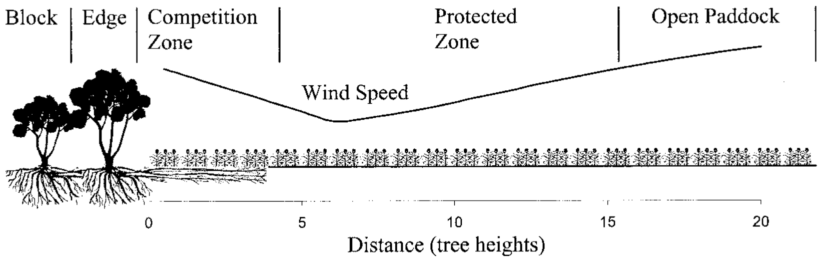

Fig. 1. Diagram of the agroforestry system under consideration. Line represents the general trend in near surface wind speed that defines the extent of the protected zone.

often greater than that of the trees in the inner rows. An analysis of this system would need to take this difference into account and so the tree belt is considered to consist of inner and edge tree zones.

Nuberg (1998), Bird (1998), Cleugh (1998) and Cleugh et al. (1998) have thoroughly described the ways in which trees may impact a neighbouring field in temperate agricultural systems. These authors suggest that in some situations the net effect of these impacts may only result in very subtle effects on crop productivity. In the low to medium rainfall areas of Australia the availability of water is likely to exert greater influence on crop productivity than variations in light or temperature due to the presence of the trees. Recent studies have highlighted the extent to which trees can alter the water balance of neighbouring cropping land (e.g. Ellis et al., 2001; White et al., 2002; Woodall and Ward, 2002). Albertsen et al. (2000) failed to identify a significant effect of aspect on pasture production next to *Eucalyptus globulus* tree belts in Western Australia and so did not include shading in their analyses.

The initial conceptualisation of the agroforestry system described in this paper will deal with only two tree–crop interactions: competition for stored soil moisture and changes in crop evaporative demand due to alterations in wind speed. The impacts of trees on the shading of crops and on air and canopy temperatures are acknowledged as important system phenomena under many agroforestry systems. However, the systems of interest in the low to medium rainfall regions of Australia are dominated by soil water deficits within the crop season. It is this competition for water that represents the initial target for APSIM simulations.

The use by trees of resources from within the field can lead to depression of crop production within the tree–crop competition zone. The extent of the yield depression will depend on many factors but these can basically be reduced to the issues of sink and source strength for soil resources. As the trees grow, the extent of their root systems within the field will increase. However, this may not necessarily lead to greater depression of crop yields. The demand for resources may increase as the trees mature but a more extensive root zone has a larger resource base from which to meet the tree demand. The ultimate effect of this competition on the crop will depend on the supply of the resource in question. In the case of water the competition of the tree for soil water will have a greater effect in a dry season than during a wet season. As a result, the interplay between crop and tree will vary with tree size and recent climatic history.

A belt of trees, when oriented to act as a windbreak, will affect the crop for a significant distance down-wind. Reduction in wind speed can lead to alterations in the microclimate of the crop that can result in enhanced growth. The extent and magnitude of this effect will vary with season, crop and type of windbreak (Cleugh, 1998). Tree height is the major determinant of the level of shelter at some point down-wind from the windbreak. In this conceptual agroforestry system, the height of the trees growing on the edge of the tree belt can be used to determine the spatial variation in wind speed for each point in space.

The final component of the system is the portion of the field that is not influenced by the windbreak. In essence, this component is no different to the other points in space. This point has to be positioned far enough away from the windbreak so as to be out of its influence on wind speed—this point is generally greater than 25 tree heights from the windbreak (Cleugh, 1998).

4. A case study using APSIM

4.1. Specification of an agroforestry system

A simple agroforestry system has been be simulated for Dalby, Qld. (27°S, 153°E) where a belt of trees (*Eucalyptus argophloia*) is positioned on the edge of a 25 ha paddock, measuring 500 m × 500 m, and where a winter crop of chickpea (*Cicer arietinum* L.) is grown each year between 1955 and 1984. The simulation was run continuously over this period. Each chickpea crop was planted based on a sowing criterion of receiving 25 mm rainfall over a 5 day period between the 1st May and 25th July using the cultivar Amethyst sown at 30 000 plants/ha. The soil used was a grey Vertosol with approximately 180 mm of plant available water to the maximum chickpea rooting depth of 1.2 m (Hochman et al., 2001).

The hypothetical windbreak consists of 1 ha on the edge of the paddock planted with *E. argophloia* at 5 × 5 m spacing resulting in 400 trees planted in four rows. The trees were sown at the beginning of this simulation in 1955 and they reached a height of approximately 25 m by the end of the simulation in 1984.

The extent of the tree–crop competition zone under such systems has been measured to be approximately equal to three times the height of the trees for *E. argophloia* (Carberry et al., 2002a). These results are similar to those obtained for trees in southern Australia (Ellis et al., 2001) but exceed those observed for sandy soils in western Australia (Sudmeyer et al., 2002). Extraction of water by tree roots within the crop area has been observed to approximately 0.9 m depth (Carberry et al., 2002a). These observations have been used in the model to specify expansion of the tree root system into neighbouring cropping land. Both edge and inner trees have access to deeper soil resources in soil directly below them (3 m). The edge zone was set to consist of only one row of trees as indicated by surveys of existing windbreaks within this region.

The following price/cost assumptions (in $US) were used in the economic analysis:

- Chickpeas: price = $210/t, variable costs $110/ha
- *E. argophloia*: price = $30/m^3 (sawlogs sold at stump). The variable costs comprised $675/ha in the establishment year (site preparation, trees, planting, pre-plant weed control, immediate post plant weed control), $337/ha in the second year (post-plant spraying, first pruning/thin) and $250/ha pruning costs in years 5, 10 and 15. In addition, $10/ha was added in years 3–30 for fire control.
- A discount rate of 6% was applied to a 30-year investment.
- Real prices for year 2001 were used with no adjustment for inflation.

4.2. APSIM configuration

APSIM version 2.1 was utilised to simulate the conceptual agroforestry system as shown in Fig. 2. APSIM was set up to consist of a main driving system with an array of subsystems representing discrete points within the two-dimensional representation of the system. The two dimensions being simultaneously simulated are: (i) the horizontal flows of wind and translocation of water and nitrogen within tree roots between adjacent points, represented in Fig. 2 by an inner tree block, an edge tree area and points 1 to *N* of crop area; and (ii) the vertical flows at each point of water, nitrogen and carbon between plants and the soil to depth.

To achieve multi-point simulation, each subsystem contained APSIM modules for the simulation of the particular plant and soil processes at that point in space. All subsystems required their own instance of the key soil modules responsible for simulation of soil water balance (APSIM-SoilWat), soil nitrogen dynamics (APSIM-SoilN) and

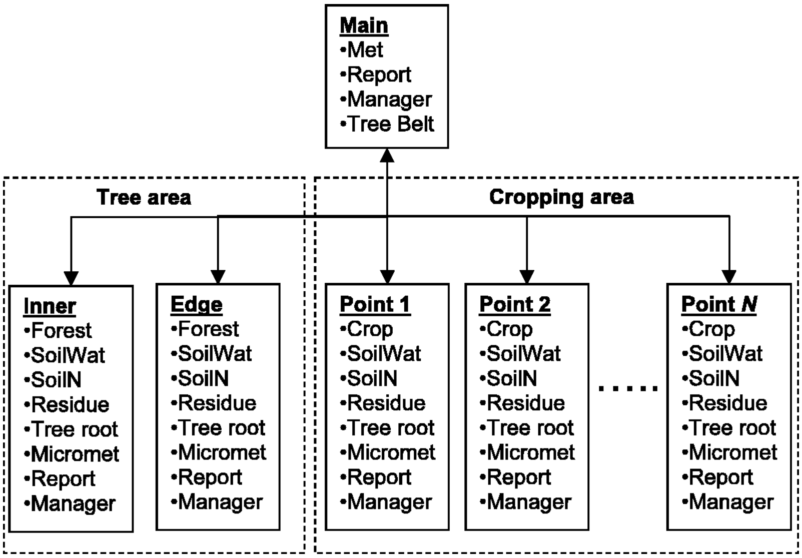

Fig. 2. Diagram of model configuration showing different instances of APSIM and the APSIM Modules used within each instance.

surface residue breakdown (APSIM-Residue). The two subsystems representing the inner and outer edge of the tree belt each contained an instance of the APSIM-Forest module to simulate tree growth. Likewise, each point within the cropping area contained an instance of the APSIM-Chickpea module (Robertson et al., 2002). All subsystems incorporated APSIM modules responsible for point-specific farmer management logic (APSIM-Manager module) and for reporting output data specific for each point (APSIM-Report module).

All subsystems also included an instance of the APSIM-Micromet module, which was responsible for calculating a potential transpiration demand term for each plant component for that point in the system using the Penman–Monteith equation. Within the cropping area, this potential transpiration term at each subsystem point was affected by daily wind speed as influenced by the adjacent tree windbreak. The relative reduction in wind speed at different distances downwind from the tree belt was based on the approach proposed by Cleugh and Hughes (2002) and employed by Meinke et al. (2002). Given the complex advective conditions down wind from a windbreak, a method for relating wind speed to aerodynamic conductance for water vapour (Cleugh, 2002) was used to capture the resultant behaviour of turbulent flow. Actual water use by the crop at each subsystem point was calculated in each instance of the APSIM-Chickpea module as the balance of potential transpiration demand, calculated by APSIM-Micromet, and soil water supply as determined in the instance of the APSIM-SoilWat module for that particular subsystem point.

The APSIM-Micromet module was also responsible for determining potential transpiration demand for the two tree subsystems. However, in the edge tree subsystem, soil water supply could be accessed from multiple subsystem points, both within the tree and cropping areas. The number of subsystem points contributing to satisfying the tree transpiration demand would also change over time as the trees grew and their root system expanded further out into the cropping area. Within each subsystem point, a tree root module (represented by the APSIM-Root module) extracted soil water in response to tree transpiration demand, calculated by APSIM-Micromet, and to soil water supply as determined by the APSIM-SoilWat module.

The main driving system contains modules with universal functionality to be communicated to all subsystems—e.g. the supply of daily weather data (APSIM-Met module) the reporting of system status (APSIM-Report module) and overall management logic for the agroforestry system (APSIM-Manager module). The main driving system also contained a tree belt module responsible for specifying the interactions between the points in space and time due to the presence of the tree belt. These interactions include uptake of soil water by the trees and local micrometeorological variations due to sheltering by the trees (in this case only altered wind speed). In this example, 17 discrete points have been included in the analysis, of which the 15 points within the cropping area have been specified to lie within 500 m of the tree belt. The simple rules for partitioning tree transpiration demand between subsystem points were based upon the soil water supply at each point and the assumption of a decrease in tree rooting intensity across its root zone proportional to the square of the distance from the tree.

4.3. Simulation results

APSIM was configured to simulate the growth of a hypothetical belt of trees positioned adjacent to annual crops of chickpea. Fig. 3 presents the simulated growth of the belt of trees over the 30-year simulation period. The differing rates of wood production from trees positioned inside the belt compared to those on the belt's edge are the result of the enhanced water supply to the edge trees in this low rainfall environment. Trees on the belt's edge are able to capture resources, mainly soil water, from the adjacent cropland. This analysis clearly demonstrates the need for separating the tree area into two functional zones. Also noticeable is the relatively constant annual growth rate of edge trees in this highly variable environment—annual rainfall for Dalby between 1955 and 1984 ranged between 380 and 1031 mm. Whereas total annual rainfall could explain over 50% of the variation in simulated annual increment in stem wood volume for the trees inside the tree belt, the correlation was much lower for the edge trees (where rainfall accounted for only 11% of the variation). The trees growing on the side of the tree belt were able to use water from the cropping land during extended dry periods to maintain relatively higher growth rates.

Fig. 4 shows how wind speed (as a fraction of open field wind speed) across the transect is simulated to be affected by the age and height of the simulated trees. As the trees grow, the extent of the shelter zone within the field increases such that, by the age of 10 years, there is a sheltered

Fig. 3. Simulated standing wood volume (over bark) of tree stems for the inner and edge trees during the 30-year simulation period.

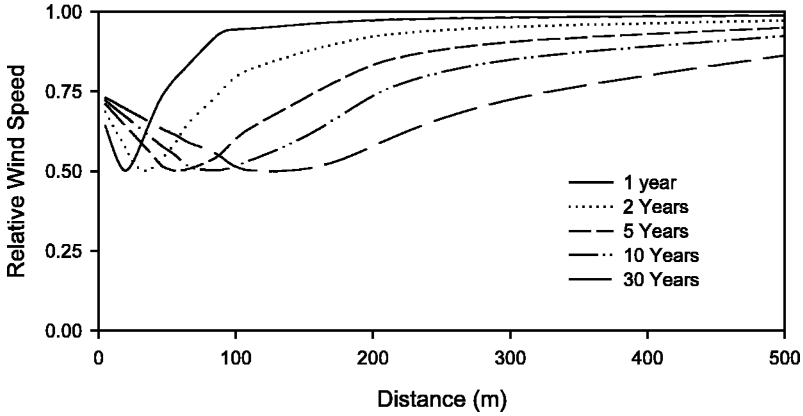

Fig. 4. Simulated wind speed (relative to open field) for up to a distance of 500 m downwind from the windbreak. Data are shown for various ages of trees up to 30 years.

zone of several hundred metres. The impact of this sheltering on subsequent crop yield is indicated in Fig. 5b. Whilst the level of yield enhancement from wind protection is quite small, the spatial extent of this increased production may result in significant overall response to the shelter.

The increased yields due to shelter will be offset by the yield depression next to the trees due to competition for water resources. Fig. 5b also shows various levels of yield depression as a result of the state of the soil, climate and tree belt. In this environment, storage of in-fallow rainfall is important for supplementing rainfall during the cropping season. Much of the competitive nature of the tree–crop interface can be found in the reduced soil water storage near the trees at sowing time (Fig. 5a). The prevailing climate and tree size led to a wide range of competitive levels simulated throughout the life of the tree belt.

The long-term benefits of planting trees on farms to protect the environment from downstream salinity impacts are indicated in Fig. 6. Reduction in drainage of water below the crop root zone is not limited to the area under the trees but extends across the entire tree root zone within the field. This closely resembles the results obtained by Ellis et al. (1999) using analyses transects of salt profiles away from trees in southern Australia. As a result, total simulated drainage loss across the field has been reduced by 7.5% by reafforestation of just 4% of the area.

4.4. Economic analysis

A simple economic analysis can illustrate the way in which APSIM-simulated data can be used to quantify the potential economic benefits and risks of planting trees as windbreaks to cropping lands in Australia. The example provided is a paddock-scale economic analysis to compare the performance of the described agroforestry system over a 30-year period with an ‘open field’ paddock of chickpeas (the benchmark) over the same period of time. Net present value (NPV) and annual net cash flow are the appropriate economic performance indicators used to evaluate this agroforestry investment case study. The use of simulated data based on long-term weather records represents an important development in Australian agroforestry economic analysis frameworks by: (a) allowing for the assessment of economic risk attributable to climate variability; and (b) providing benchmarks for comparisons of with/without scenarios. The currently promoted economic analysis tool for exploring agroforestry options in Australia, The Agroforestry Calculator (Eckersley, 2000), necessitates the user to nominate average annual production figures for the analysed system.

Net present values for the agroforestry system and open field benchmark for the 30-year period are summarised in Table 1. To highlight the effect of discounting on the performance of each investment, the same summed net cash flows without

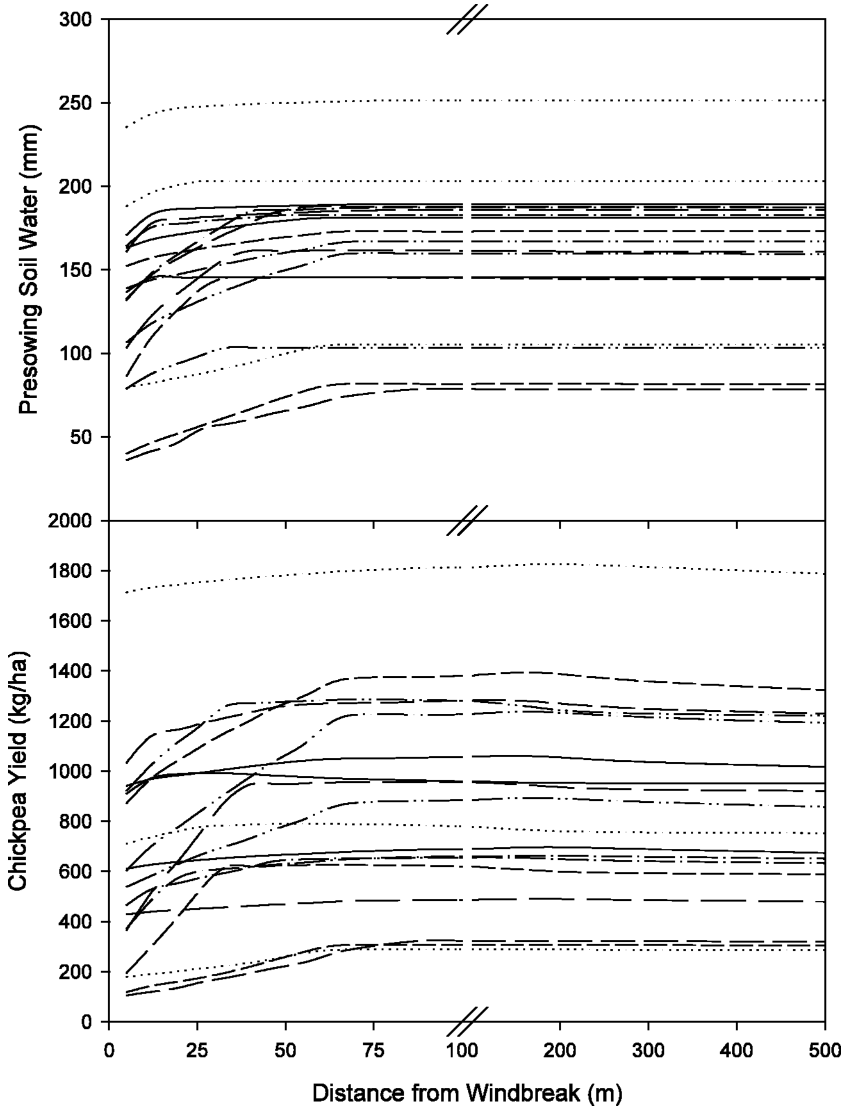

Fig. 5. Pre-sowing extractable soil water and chickpea yield for up to 500 m down wind from a windbreak. Each line represents a different season within the 30-year simulation period. Note the break in the X-axis.

discounting are also presented. Sensitivity testing is performed for three establishment costs. Because the discounting process erodes the value of future cash flows, establishment costs, which are incurred at the start of the investment period, could be expected to have the most significant impact on the NPV and on the time taken for the paddock to generate positive cumulative net cash flows, also known as the payback period. For a more complete assessment of the system, sensitivity testing should also be performed on other variables such as crop and timber prices.

While simply totalling the net cash flows of the two systems indicates that agroforestry generates at least $5500 of extra net income, the corresponding NPVs indicate that the annual cropping option is the marginally better performing system in this instance. This occurs because the discounting process erodes the value of income generated from trees at the end of the investment period.

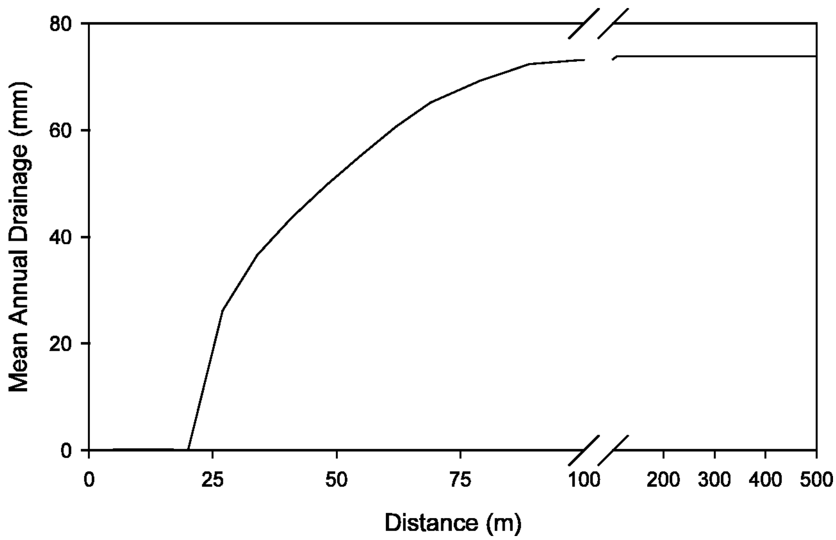

Fig. 6. Mean annual drainage below 2.7 m for a 500 m transect from the edge of the paddock. The tree belt is 20 m wide. Trees reached a height of approximately 25 m by age 30 years. Note the break in the X-axis.

The large lag period between the time of capital outlay and return from the investment is a critically important issue for farmers to consider. Over the 30-year period, the differences in establishment costs did not appear to have a major impact on NPV. However, the short-term effects on cash flow are more significant.

Annual and cumulative net cash flows are presented in Fig. 7. For both systems, annual net cash flows display year-to-year volatility. Cumulative cash flows for the agroforestry system do not catch up to the benchmark system until the final year of the investment period when trees are sold. The annual difference between the cash flows for years 1–29 is shown in Fig. 7c. The final year cash flow difference of $9160 is omitted from this graph to allow the axis to be restricted to a range of net incomes permitting closer examination of the variations. For the assumed prices and costs, there are no years for which cash flows for the agroforestry system are higher than for the benchmark. This indicates that increases in production due to crop sheltering are not high enough to account for the reduced cropping area and reduced yield next to the trees. In years when tree management expenses are not incurred, the difference in cash flows between the two systems is usually small. However, excluding the establishment year, income for the agroforestry system was up to $350 dollars less than the benchmark system.

Table 1
Net present Values for the agroforestry system, the open field benchmark and the difference (agroforestry NPV-benchmark NPV) for three establishment costs

Establishment cost ($/ha)	Discounted returns			Equivalent, non-discounted returns		
	NPV ($) agroforestry	NPV ($) benchmark	Difference ($)	NPV ($) agroforestry	($) NPV Benchmark	Difference ($)
450	15 918	16 178	260	36 656	30 568	6088
675	15 692	16 178	485	36 431	30 568	5863
1000	15 368	16 178	810	36 106	30 568	5538

NPV is reported in $US.

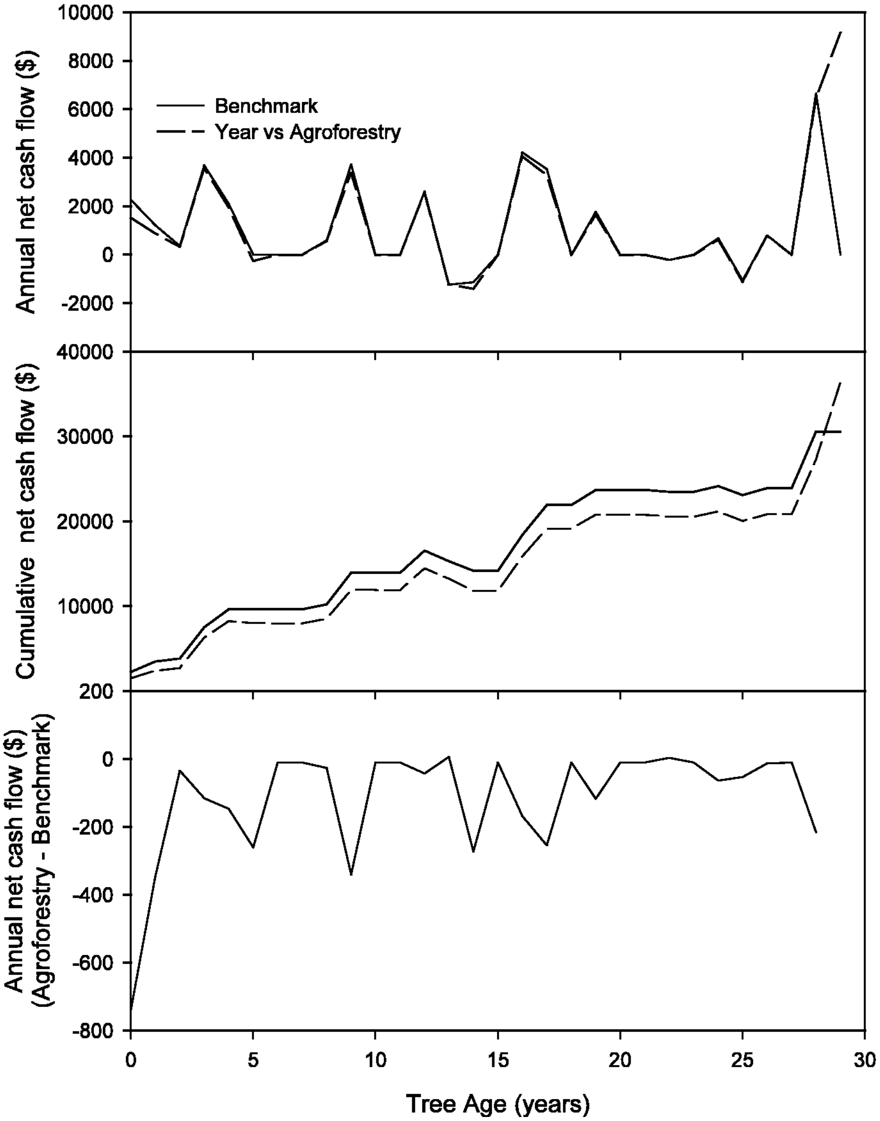

Fig. 7. Cash flow for a 30-year tree belt growing cycle. (a) Annual cash flow for benchmark system (—) and agroforestry system (---); (b) cumulative cash flow (symbols as for a); and (c) difference in annual cash flow between benchmark and agroforestry systems for years 1–29 of the investment.

5. Conclusions

This paper described the emerging capability within the APSIM simulation framework to simulate a two-dimensional system, with agroforestry used as the case study example. The modern software design principles employed in the latest version of APSIM (Keating et al., 2003) now facilitate a user to simulate complex agricultural systems by employing a library of dedicated crop and soil modules and systems configuration capabilities that address both temporal and spatial configurations. Whilst many of the concepts described in this paper, such as abstracting the system into functional units, are not new to the simulation of agroforestry systems (Van Noordwijk and Lusiana, 1999; Qi et al., 2001; Mayus et al., 1999a), the APSIM framework provides an integrated approach to addressing not only agroforestry but many different configurations for agricultural systems.

The availability in APSIM of process-level modules for tree, crop, soil and atmospheric components enables considerable flexibility for specifying interactions between the tree–crop components of an agroforestry system. In the case study reported here it was possible to use the state of the detailed APSIM-Forest module to dynamically calculate effects on the neighbouring field on a daily basis—such effects included both windbreak and tree competition impacts. Carberry et al. (2002b) previously had to assume a set percentage crop loss from tree–crop competition in their analysis of the economics of tree windbreaks in Australia. The use of a proven soil water balance module enabled a detailed water balance assessment to be made for the simulation case study, including quantifying the impact of a tree windbreak on deep drainage. The capabilities of the dynamic tree and crop modules in APSIM also allowed a simple economic analysis to be performed for the system under investigation. In contrast, Brandle et al. (1992) employed NVP analysis to explore the long-term economics of windbreak systems in the USA, but this analysis was limited by having to use assumed yield scenarios. This same limitation is evident in economic analysis tools currently used in Australia (Eckersley, 2000).

The economic analysis undertaken within the example case study illustrated how APSIM-simulated data can be incorporated into an economic analysis to quantify the potential benefits and risks of planting trees as windbreaks to cropping lands in Australia. In a risky production environment, such as the low to medium rainfall regions of Australia, year-to-year cash flow variability is an important concern to Australian farmers. The ability to incorporate climate-driven production variability into economic analysis is therefore a valuable capability. When conducting an economic analysis of an agroforestry investment, the key questions is ‘with what do I compare the results?’. The use of simulated data allows for the establishment of benchmarks against which alternatives can be properly assessed, e.g. no agroforestry versus agroforestry. However, these analyses still do not address the complete impacts of agroforestry systems because they ignore externalities to the production system—e.g. the planting of trees may lessen the risk of dryland salinity which will have an economic benefit in the long-term. Such broader economic considerations are of current interest in Australia and will be a focus for our continuing research and model applications.

Clearly, this report of APSIM’s new capability for simulating agroforestry systems needs to be followed by reports on its simulation performance against observed data. Several components have been so tested—e.g. for tree growth (Huth et al., 2001), tree water balance (Snow et al., 1999) and windbreak impacts (Meinke et al., 2002)—but not for a complete agroforestry system. A significant limitation to achieving this objective has been the paucity of comprehensive measured data on agroforestry systems in Australia. There are several current initiatives to redress this situation.

Expanding the range of important phenomena to be simulated by APSIM under agroforestry systems is a further requirement in making the simulations more realistic. For example, Mayus et al. (1999a,b) included shading in their modelling of windbreak systems in the Sahel. Their simulation analysis indicated a significant impact on the crop due to shading. However, shading impacts were only observed very close to the trees and were not significant in a dry season. The initial configuration of APSIM for agroforestry systems reported in this paper did not incorporate the impacts of shading. Such impacts are argued as being less important in the drier areas of Australia where farmers normally leave a reasonable non-planted buffer between trees and crops. However, the simulation of further impacts of trees on neighbouring crops—such shading, crop damage, changes in temperature and humidity, and interception of rainfall—will need to be investigated as relevant field data become available for the systems being studied in the low rainfall areas of Australia.

Investing in commercial agroforestry is risky, especially in the medium to low rainfall regions of Australia. The tradeoffs involved with such a change in a farming system can also be difficult to determine. The ability to combine economic analysis with both crop and tree simulation capabilities within a simple spatial context provides a powerful tool for evaluating various agroforestry options. This same tool can be re-deployed for simulating tree–crop interactions for a range of site, soil, climate, crop or windbreak designs. In many ways, the data requirements for such a model configuration are not significantly different to those for standard application of the APSIM model to a single-point problem. This combined bio-economic framework (APSIM and NPV analysis) has been used successfully with farmers in Australia who are contemplating agroforestry investment options (Carberry et al., 2002a). The intention now is to further test and use APSIM with individual landholders to quantitatively assess the viability of integrating agroforestry and crop production in ways where they can explore such investment in the context of their own farms.

Acknowledgements

The authors wish to thank Dr Helen Cleugh for her contributions to the simulation of windbreak impacts on crop growth and Dean Holzworth for advice for the multi-point simulations of the tree–crop competition zone. Parts of this research have been supported by the Rural Industries Research and Development Corporation (RIRDC) and Land and Water Australia (LWA).

References

Albertsen, T., Eckersley, P., Blennerhassett, S., Moore, R., Hingston, R., 2000. Bluegum Timberbelt Design for Alley Farming. A report for the Rural Industries Research and Development Corporation. RIRDC Publication No 00/154

Bird, P.R., 1998. Tree windbreaks and shelter benefits to pasture in temperate grazing systems. Agroforestry Syst. 41, 35–54.

Boote, K.J., Jones, J.W., Hoogenboom, G., Pickering, N.B., 1998. The CROPGRO model for grain legumes. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer, Dordrecht, pp. 99–128.

Brandle, J.R., Johnson, B.B., Akeson, T., 1992. Field windbreaks: are they economical? J. Prod. Agric. 5, 393–398.

Carberry, P.S., Adiku, S.G.K., McCown, R.L., Keating, B.A., 1996. Application of the APSIM cropping systems model to intercropping systems. In: Ito, O., Johansen, C., Adu-Gyamfi, J.J., Katayama, K., Kumar Rao, J.V.D.K., Rego, T.J. (Eds.), Dynamics of Roots and Nitrogen in Cropping Systems of the Semi-Arid Tropics. Japan International Research Center for Agricultural Sciences, International Agricultural Series No. 3, pp. 637–648.

Carberry, P.S., Huth, N.I., Poulton, P.L., Brennan, L.E., 2002a. Quantifying the tradeoff between tree and crop productivity on farms. A report for the Rural Industries Research and Development Corporation/Land and Water Australia/Forest and Wood Products Research and Development Corporation Joint Venture Agroforesty Program. RIRDC Publication (in press).

Carberry, P.S., Meinke, H., Poulton, P.L., Hargreaves, J.N.G., Snell, A.J., Sudmeyer, R.A., 2002b. Modelling crop growth and yield under the environmental changes induced by windbreaks 2. Simulation of potential benefits at selected sites in Australia. Aust. J. Exp. Agric. 42, 887–900.

Cleugh, H.A., 1998. Effects of windbreaks on airflow, microclimate and crop yields. Agroforestry Syst. 41, 55–84.

Cleugh, H.A., 2002. Parameterising the impact of shelter on crop microclimates and evaporation fluxes. Aust. J. Exp. Agric. 42, 859–874.

Cleugh, H.A., Hughes, D.E., 2002. The impact of shelter in crop microclimates: A synthesis of results from wind tunnel and field experiments. Aust. J. Exp. Agric. 42, 679–701.

Cleugh, H.A., Miller, J.M., Böhm, M., 1998. Direct mechanical effects of wind on crops. Agroforestry Syst. 41, 85–112.

Eckersley, P., 2000. The Agroforestry Calculator: User manual. A report for the Rural Industries Research and Development Corporation; RIRDC Publication No 99/154, p. 24.

Ellis, T., Hatton, T., Nuberg, I., 1999. A simple method for estimating recharge from low rainfall agroforestry systems. In: Musey, A., Santos Pereira, L., Fritsch, M. (Eds.), Envirowater99, 2nd Inter-regional Conference on Environment-Water, 1–4 September, Laussane, Switzerland. Presses Polytechniques et Universitaires Romandes, Lausane.

Ellis, T., Bessard, Y., Brophy, J. 2001. Estimating recharge from alley farms: Applying the ENOR model within the Murray Darling Basin. CSIRO Land and Water Technical Report 4/01, CSIRO Australia, April 2001.

Friend, A.D., Stevens, A.K., Knox, R.G., Cannell, M.G.R., 1997. A process-based, terrestrial biosphere model of ecosystem dynamics (Hybrid v3.0). Ecol. Model. 95, 249–287.

Fry, G.J., Lungu, C., 1996. Assessing the benefits of interventions to improve soil moisture conditions using the PARCH

Crop Environment Model. In Land degradation: a challenge to agricultural production. Proceedings 5th Annual Scientific Conference, SADC-land and water management research programme, Harare, Zimbabwe, 10–14 October, 1994, pp. 119–125.
Hochman, Z., Coutts, J., Carberry, P.S., McCown, R.L., 2000. The FARMSCAPE experience. Simulations aid participative learning in risky farming systems in Australia. In: Cerf, M., Gibbon, D., Hubert, B., Ison, R., Jiggins, J., Paine, M., Proost, J., Röling, N. (Eds.), Cow up a Tree: Knowing and Learning for Change in Agriculture. Case Studies from Industrialised Countries. Coll. Science Update, INRA Editions, Paris, pp. 175–188.
Hochman, Z., Dalgliesh, N.P., Bell, K., 2001. Contributions of soil and crop factors to plant available soil water capacity of annual crops on black and grey Vertosols. Aust. J. Agric. Res. 52, 7–14.
Huth, N.I., Snow, V.O., Keating, B.A., 2001. Integrating a forest modelling capability into an Agric. production systems modelling environment-current applications and future possibilities. Proceedings of the International Congress on Modelling and Simulation, Aust. National University, Dec. 2001, pp. 1895–1900.
Jones, J.W., Keating, B.A., Porter, C., 2001. Approaches for modular model development. Agric. Syst. 70, 421–443.
Keating, B.A., Asseng, S., Brown, S.D., Carberry, P.S., Chapman, S., Dimes, J.P., Freebairn, D.M., Hammer, G.L., Hargreaves, J.N.G., Hochman, Z., Holzworth, D., Huth, N.I., Meinke, H., McCown, R.L., Probert, M.E., Robertson, M.J., Silburn, M., Smith, C.J., Snow, V.O., Verburg, K., Wang, E., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. (in press).
Lawson, G.J., Crout, N.M.J., Levy, P.E., Mobbs, D.C., Wallace, J.S., Cannell, M.G.R., Bradley, R.G., Sinclair, F., 1995. The tree–crop interface: representation by coupling of forest and crop process-models. Agroforestry Syst. 30, 199–221.
Matthews, R.B., Hunt, L.A., 1994. GUMCAS: a model describing the growth of cassava (*Manihot esculenta* L. Crantz). Field Crops Res. 36, 69–84.
Matthews, R.B., Lawson, G.J., 1997. Structure and applications of the HyCas model. Agroforestry Forum 8, 14–17.
Mayus, M., Van Keulen, H., Stroosnijder, L., 1999a. Analysis for dry and wet years with the WIMISA model of tree–crop competition for windbreak systems in the Sahel. Agroforestry Syst. 43, 203–215.
Mayus, M., Van Keulen, H., Stroosnijder, L., 1999b. A model of tree–crop competition for windbreak systems in the Sahel: description and evaluation. Agroforestry Syst. 43, 183–201.
McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P., Freebairn, D.M., 1996. APSIM: A novel software system for model development, model testing, and simulation in Agricultural Systems Research. Agric. Syst. 50, 255–271.
McCown, R.L., Carberry, P.S., Foale, M.A., Hochman, Z., Coutts, J.A., Dalgliesh, N.P., 1998. The FARMSCAPE approach to farming systems research. Proceedings of the 9th Aust. Society of Agronomy Conference. Aust. Society of Agronomy, Wagga Wagga, NSW, pp. 633–636.
Meinke, H., Carberry, P.S., Cleugh, H., Poulton, P.L., Hargreaves, J.N.G., 2002. Modelling crop growth and yield under the environmental changes induced by windbreaks 1. Model development and validation. Aust J. Exp. Agric. 42, 875–885.
Mobbs, D.C., Crout, N.M.J., Lawson, G.J., Cannell, M.G.R., 1997. Structure and applications of the HyPAR model. Agroforestry Forum 8, 10–14.
Muetzelfeldt, R., Taylor, J., 1997. The suitability of AME (the Agroforestry Modelling Environment) for agroforestry modelling. Agroforestry Forum 8, 7–9.
NLWRA, 2000. Dryland Salinity. Australia's dryland salinity assessment 2000. National Land and Water Resources Audit ISBN 0 642 37106 7. Nov 2000.
Nuberg, I.K., 1998. Effect of shelter on temperate crops: a review to define research for Australian conditions. Agroforestry Syst. 41, 3–34.
Prinsley, R.T., 1992. The role of trees in sustainable agriculture—an overview. Agroforestry Syst. 40, 87–115.
Qi, X., Mize, C.W., Batchelor, W.D., Takle, E.S., Litvina, I.V., 2001. SBELTS: a model of soybean production under tree shelter. Agroforestry Syst. 52, 53–61.
Robertson, M.J., Carberry, P.S., Huth, N.I., Turpin, J.E., Probert, M.E., Poulton, P.L., Bell, M., Wright, G.C., Yeates, S.J., Brinsmead, R.B., 2002. Simulation of growth and development of diverse legume species in APSIM. Aust. J. Agric. Res. 53, 429–446.
Snow, V.O., Bond, W.J., Myers, B.J., Theiveyanathan, S., Smith, C.J., Benyon, R.G., 1999. Modelling the water balance of effluent-irrigated trees. Agric. Water Manage. 39, 47–67.
Stirzaker, R., Vertessy, R., Sarre, A. (Eds.), 2002. Trees, water and salt: An Australian guide to using trees for healthy catchments and productive farms. Joint Venture Agroforestry Program, RIRDC Publication number 01/086.
Sudmeyer, R., Hall, D., Eastham, J., Adams, M., 2002. The tree/crop interface: the effects of root-pruning in south western Australia. Aust. J. Exp. Ag. 42, 763–772.
Wallace, J.S., 1996. Modelling component transpiration in mixed plant communities. Evapotranspiration and irrigation scheduling. Proceedings of the International Conference, San Antonio, Texas, USA, November 3–6 1996, pp. 585–591.
Wang, Y.P., Jarvis, P.G., 1990. Description and validation of an array model—MAESTRO. Agric. For. Meteorol. 51, 257–280.
White, D.A., Dunin, F.X., Turner, N.C., Ward, B.H., Galbraith, J.H., 2002. Water use by contour-planted belts of trees comprised of four *Eucalyptus* species. Agric. Water Manage. 53, 133–152.

Woodall, G.S., Ward, B.H., 2002. Soil water relations, crop production and root pruning of a belt of trees. Agric. Water Manage. 53, 153–169.
Wright, S.L., Veraart, V.E., Moore, A., Keating, B.A., 1997. A Software Protocol for Connecting Different Crop, Soil and Pasture Simulation Models. American Society Agronomy Abstracts, Anaheim, CA, p. 21.
Van Noordwijk, M., Lusiana, B., 1999. WaNuLCAS, a model of water, nutrient and light capture in agroforestry systems. Agroforestry Syst. 43, 217–242.